Time and Matter in the Interaction between Gravity and Quantum Fluids: Are there Macroscopic Quantum Transducers between Gravitational and Electromagnetic waves?

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Abstract

Measurements of the tunneling time are briefly reviewed. Next, time and matter in general relativity and quantum mechanics is examined. In particular, the question arises: How does gravitational radiation interact with a coherent quantum many-body system (a "quantum fluid")? A minimal coupling rule for the coupling of the electron spin to curved spacetime in general relativity implies the possibility of a coupling between electromagnetic (EM) and gravitational (GR) radiation mediated by a quantum Hall fluid. This suggests that quantum transducers between these two kinds of radiation fields might exist. We report here on a first attempt at a Hertz-type experiment, in which a high-T_c superconductor (YBCO) was the material used as a quantum transducer to convert EM into GR microwaves, and a second piece of YBCO in a separate apparatus was used to back-convert GR into EM microwaves. An upper limit on the conversion efficiency of YBCO was measured to be 1.6×10^{-5}.

1   Introduction

In this conference in Venice on "Time and Matter," one of us (RYC), was invited to speak on the tunneling time problem: How quickly does a particle traverse a barrier in the quantum process of tunneling? A. M. Steinberg, P. G. Kwiat, and RYC have used a photon-pair emission light source (spontaneous parametric down-conversion) for measuring the single-photon tunneling time, using the "click" of a Geiger counter as the registration of when one photon, which had succeeded in tunneling

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through the barrier, reached the detector, relative to a second, vacuum-traversing photon, which was born at the same time as the first photon (hence its "twin"). The arrival time of the tunneled photon was measured with respect to that of its twin, which had traversed a distance equal to the tunnel barrier thickness, but in the vacuum, by means of the difference in the two "click" times of two Geiger counters. These two Geiger counters were used in the coincidence detection of the two photons, with one counter placed behind the tunnel barrier, and the other counter placed behind the vacuum, in conjunction with a Hong-Ou-Mandel interferometer.

By means of this two-photon interferometer, we achieved the sub-picosecond time resolution necessary for measuring the tunneling time of a photon relative to the vacuum-traversal time of its twin. The result was that the Wigner theory of tunneling time was confirmed to be the one that applied to our experiment. The surprising result was that when a photon succeeded in tunneling (which is rare), it arrived earlier than its twin which had traversed the vacuum, as indicated by the fact that the "clicks" of the Geiger counter registering the arrival of the tunneling photons occurred earlier on the average than the Geiger counter "clicks" registering the arrival of the vacuum-traversing twin photons, as if the tunneling photons had traversed the tunnel barrier superluminally. The effective group velocity of the tunneling single-photon wavepacket was measured to be 1.7 ± 0.2 times the vacuum speed of light.

Since our tunneling-time work has already been adequately reviewed,[1] here we shall concentrate instead on a different question concerning "Time and Matter," namely, the role of time in the interaction of gravity, in particular, of gravitational radiation, with matter in the form of quantum fluids, i.e., many-body systems which exhibit off-diagonal long-range order (ODLRO), such as superconductors, superfluids, atomic Bose-Einstein condensates (BECs), and quantum Hall fluids.[2] As we shall see, under the proper circumstances, there results the interesting possibility that such quantum fluids could in principle mediate the conversion of EM into GR waves, and vice versa.

2 Quantum fluids as antennas for gravitational radiation

Can quantum fluids circumvent the problem of the tiny rigidity of classical matter, such as that of the normal metals used in Weber bars, in their feeble responses to gravitational radiation? One consequence of the tiny rigidity of classical matter is the fact that the speed of sound in a Weber bar is typically five orders of magnitude less than the speed of light. In order to transfer energy coherently from a gravitational wave by classical means, for example, by acoustical modes inside the bar to some local detector, e.g., a piezoelectric crystal glued to the middle of the bar, the length scale L of the Weber bar is limited to a distance scale on the order of the speed of sound times the period of the gravitational wave, i.e., an acoustical wavelength λ_{sound}, which is typically five orders of magnitude

smaller than the gravitational radiation wavelength λ to be detected. This makes the Weber bar, which is thereby limited in its length to $L \simeq \lambda_{sound}$, much too short an antenna to couple efficiently to free space.

However, rigid quantum objects, such as a two-dimensional electron gas in a strong magnetic field which exhibits the quantum Hall effect, in what Laughlin has called an "incompressible quantum fluid",[3] are not limited by these classical considerations, but can have macroscopic quantum phase coherence on a length scale L on the same order as (or even much greater than) the gravitational radiation wavelength λ. The origin of this rigidity is that the phase of the wavefunction must remain rigidly single-valued everywhere inside the quantum fluid, whenever the many-body system is perturbed by gravity waves whose time variations are slow compared to the time scale of the gap time $\hbar/E_{gap}$, where E_{gap} is the energy gap separating the ground state from all excited states. Then the wavefunction will remain adiabatically, and hence rigidly, in its ground state during these time variations. Since the radiation efficiency of a quadrupole antenna scales as the length of the antenna L to the fourth power when $L << \lambda$, such quantum antennas should be much more efficient in coupling to free space than classical ones like the Weber bar by a factor of $(\lambda/\lambda_{sound})^4$.

Weinberg gives a measure of the radiative coupling efficiency η_{rad} of a Weber bar of mass M, length L, and velocity of sound v_{sound}, in terms of a branching ratio for the emission of gravitational radiation by the Weber bar, relative to the emission of heat, i.e., the ratio of the *rate* of emission of gravitational radiation Γ_{grav} relative to the *rate* of the decay of the acoustical oscillations into heat Γ_{heat}, which is given by[4]

$$\eta_{rad} \equiv \frac{\Gamma_{grav}}{\Gamma_{heat}} = \frac{64GMv_{sound}^4}{15L^2c^5\Gamma_{heat}} \simeq 3 \times 10^{-34} \ , \tag{1}$$

where G is Newton's constant. The quartic power dependence of the efficiency η_{rad} on the velocity of sound v_{sound} arises from the quartic dependence of the coupling efficiency to free space of a quadrupole antenna upon its length L, when $L << \lambda$.

The long-range quantum phase coherence of a quantum fluid allows the typical size L of a quantum antenna to be comparable to the wavelength λ. Thus the phase rigidity of the quantum fluid allows us in principle to replace the velocity of sound v_{sound} by the speed of light c. Therefore, quantum fluids can be more efficient than Weber bars, based on the v_{sound}^4 factor alone, by twenty orders of magnitude, i.e.,

$$\left(\frac{c}{v_{sound}}\right)^4 \simeq 10^{20} \ . \tag{2}$$

Hence quantum fluids could be much more efficient receivers of this radiation than Weber bars for detecting astrophysical sources of gravitational radiation. This has previously been suggested to be the case for superfluids and superconductors.[5],[6]

Another important property of quantum fluids lies in the fact that they can possess an extremely low dissipation coefficient Γ_{heat}, as can be inferred, for example, by the existence of persistent currents in superfluids

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that can last for indefinitely long periods of time. Thus the impedance matching of the quantum antenna to free space,[7] or equivalently, the branching ratio η_{rad} can be much larger than that calculated above for the classical Weber bar. Since it is difficult to calculate Γ_{heat}, we need to measure η_{rad} experimentally.

3   Minimal-coupling rule for a quantum Hall fluid

The electron, which possesses charge e, rest mass m, and spin $s = 1/2$, obeys the Dirac equation. The nonrelativistic, interacting, fermionic many-body system, such as that in the quantum Hall fluid, should obey the minimal-coupling rule which originates from the covariant-derivative coupling of the Dirac electron to curved spacetime, viz. (using the Einstein summation convention),[4],[8]

$$p_\mu \rightarrow p_\mu - eA_\mu - \frac{1}{2}\Sigma_{AB}\omega_\mu^{AB} \tag{3}$$

where p_μ is the electron's four-momentum, A_μ is the electromagnetic four-potential, Σ_{AB} are the Dirac γ matrices in curved spacetime with tetrad (or vierbein) A, B indices, and ω_μ^{AB} are the components of the spin connection

$$\omega_\mu^{AB} = e^{A\nu}\nabla_\mu\, e^B{}_\nu \tag{4}$$

where $e^{A\nu}$ and $e^B{}_\nu$ are tetrad four-vectors, which are sets of four orthogonal unit vectors of spacetime, such as those corresponding to a local inertial frame.

The vector potential A_μ leads to a quantum interference effect, in which the gauge-invariant Aharonov-Bohm phase becomes observable. Similarly, the spin connection ω_μ^{AB}, in its Abelian holonomy, should also lead to a quantum interference effect, in which the gauge-invariant Berry phase[9] becomes observable. The following Berry phase picture of a spin coupled to curved spacetime leads to an intuitive way of understanding why there could exist a coupling between a classical GR wave and a classical EM wave mediated by the quantum Hall fluid.

Due to its gyroscopic nature, the spin vector of an electron undergoes *parallel transport* during the passage of a GR wave. The spin of the electron is constrained to lie inside the space-like submanifold of curved spacetime. This is due to the fact that we can always transform to a comoving frame, such that the electron is at rest at the origin of this frame. In this frame, the spin of the electron must be purely a space-like vector with no time-like component. This imposes an important *constraint* on the motion of the electron's spin, such that whenever the space-like submanifold of spacetime is disturbed by the passage of a gravitational wave, the spin must remain at all times *perpendicular* to the local time axis. If the spin vector is constrained to follow a conical trajectory during the passage of the gravitational wave, the electron picks up a Berry phase proportional to the solid angle subtended by this conical trajectory after one period of the GR wave.

In a manner similar to the persistent currents induced by the Berry phase in systems with off-diagonal long-range order,[10] such a Berry phase induces an electrical current in the quantum Hall fluid, which is in a macroscopically coherent ground state.[11] This current generates an EM wave. Thus a GR wave can be converted into an EM wave. By reciprocity, the time-reversed process of the conversion from an EM wave to a GR wave must also be possible.

In the nonrelativistic limit, the four-component Dirac spinor is reduced to a two-component spinor. While the precise form of the nonrelativistic Hamiltonian is not known for the many-body system in a weakly curved spacetime consisting of electrons in a strong magnetic field, I conjecture that it will have the form

$$H = \frac{1}{2m} \left(p_i - eA_i - \frac{1}{2}\sigma_{ab}\Omega_i^{ab} \right)^2 + V \tag{5}$$

where i is a spatial index, a, b are spatial tetrad incides, σ_{ab} is a two-by-two matrix-valued tensor representing the spin, and $\sigma_{ab}\Omega_i^{ab}$ is the nonrelativistic form of $\Sigma_{AB}\omega_\mu^{AB}$. Here H and V are two-by-two matrix operators on the two-component spinor electron wavefunction in the nonrelativistic limit. The potential energy V includes the Coulomb interactions between the electrons in the quantum Hall fluid. This nonrelativistic Hamiltonian has the form

$$H = \frac{1}{2m} \left(\mathbf{p} - \mathbf{a} - \mathbf{b} \right)^2 + V \ , \tag{6}$$

where the particle index, the spin, and the tetrad indices have all been suppressed. Upon expanding the square, it follows that for a quantum Hall fluid of uniform density, there exists a cross-coupling or interaction Hamiltonian term of the form

$$H_{int} \sim \mathbf{a} \cdot \mathbf{b} \ , \tag{7}$$

which couples the electromagnetic $\mathbf{a}$ field to the gravitational $\mathbf{b}$ field. In the case of time-varying fields, $\mathbf{a}(t)$ and $\mathbf{b}(t)$ represent EM and GR radiation, respectively.

In first-order perturbation theory, the quantum adiabatic theorem predicts that there will arise the cross-coupling energy between the two radiation fields mediated by this quantum fluid

$$\Delta E \sim \langle \Psi_0 | \mathbf{a} \cdot \mathbf{b} | \Psi_0 \rangle \tag{8}$$

where $|\Psi_0\rangle$ is the unperturbed ground state of the system. For the adiabatic theorem to hold, there must exist an energy gap E_{gap} (e.g., the quantum Hall energy gap) separating the ground state from all excited states, in conjunction with a time variation of the radiation fields which must be slow compared to the gap time $\hbar/E_{gap}$. This suggests that under these conditions, there might exist an interconversion process between these two kinds of classical radiation fields mediated by this quantum fluid, as indicated in Fig.1.

The question immediately arises: EM radiation is fundamentally a spin 1 (photon) field, but GR radiation is fundamentally a spin 2 (graviton) field. How is it possible to convert one kind of radiation into the other,

EM wave in   GR wave out

Quantum fluid

(a)

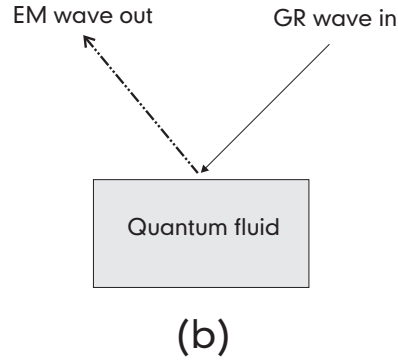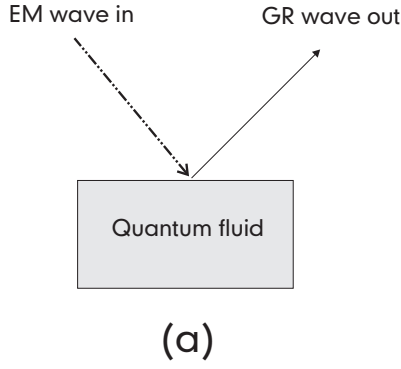EM wave out   GR wave in

Quantum fluid

(b)

Figure 1: Quantum transducer between electromagnetic (EM) and gravitational (GR) radiation, consisting of a quantum fluid, such as the quantum Hall fluid, which possesses charge and spin. The minimal-coupling rule for an electron coupled to curved spacetime via its charge and spin, results in two processes. In (a) an EM plane wave is converted upon reflection from the quantum fluid into a GR plane wave; in (b), which is the reciprocal or time-reversed process, a GR plane wave is converted upon reflection from the quantum fluid into an EM plane wave.

and not violate the conservation of angular momentum? The answer: The EM wave converts to the GR wave *through a medium.* Here specifically, the medium of conversion consists of a strong DC magnetic field applied to a system of electrons. This system possesses an axis of symmetry pointing along the magnetic field direction, and therefore transforms like a spin 1 object. When coupled to a spin 1 (circularly polarized) EM radiation field, the total system can in principle produce a spin 2 (circularly polarized) GR radiation field, by the addition of angular momentum. However, it remains an open question as to how strong this interconversion process is between EM and GR radiation. Most importantly, the size of the conversion efficiency of this transduction process needs to be determined by experiment.

We can see more clearly the physical significance of the interaction Hamiltonian $H_{int} \sim \mathbf{a} \cdot \mathbf{b}$ once we convert it into second quantized form and express it in terms of the creation and annihilation operators for the positive frequency parts of the two kinds of radiation fields, as in the theory of quantum optics, so that in the rotating-wave approximation

$$H_{int} \sim a^{\dagger} b + b^{\dagger} a , \tag{9}$$

where the annihilation operator a and the creation operator $a^{\dagger}$ of the single classical mode of the plane-wave EM radiation field corresponding the $\mathbf{a}$ term, obey the commutation relation $[a, a^{\dagger}] = 1$, and where the annihilation operator b and the creation operator $b^{\dagger}$ of the single classical mode of the plane-wave GR radiation field corresponding to the $\mathbf{b}$ term, obey the commutation relation $[b, b^{\dagger}] = 1$. (This represents a crude, first attempt at quantizing the gravitational field, which applies only in the case of weak, linearized gravity.) The first term $a^{\dagger} b$ then corresponds to the process in which a graviton is annihilated and a photon is created inside the quantum fluid, and similarly the second term $b^{\dagger} a$ corresponds to the reciprocal process, in which a photon is annihilated and a graviton is created inside the quantum fluid.

One may ask whether there exists *any* difference in the response of quantum fluids to tidal fields in gravitational radiation, and the response of classical matter, such as the lattice of ions in a superconductor, for example, to such fields. The essential difference between quantum fluids and classical matter is the presence or absence of macroscopic quantum interference. In classical matter, such as in the lattice of ions of a superconductor, decoherence arising from the environment destroys any such quantum interference. Hence, the response of quantum fluids and of classical matter to these fields will therefore differ from each other.[2]

In the case of superconductors, Cooper pairs of electrons possess a macroscopic phase coherence, which can lead to an Aharonov-Bohm-type interference absent in the ionic lattice. Similarly, in the quantum Hall fluid, the electrons will also possess macroscopic phase coherence,[11] which can lead to Berry-phase-type interference absent in the lattice. Furthermore, there exist ferromagnetic superfluids with intrinsic spin,[12] in which an ionic lattice is completely absent, such in superfluid helium 3. In such ferromagnetic quantum fluids, there exists no ionic lattice to give rise to any classical response which could prevent a quantum response to tidal gravitational radiation fields. The Berry-phase-induced response of the

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ferromagnetic superfluid arises from the spin connection (see the above minimal-coupling rule, which can be generalized from an electron spin to a nuclear spin), and leads to a purely quantum response to this radiation. The Berry phase induces time-varying macroscopic quantum flows in this ferromagnetic ODLRO system,[10] which transports time-varying orientations of the nuclear magnetic moments, and thus generates EM waves. This ferromagnetic superfluid can therefore also in principle interconvert GR into EM radiation, and vice versa, in a manner similar to the case discussed above for the ferromagnetic quantum Hall fluid. Thus there may be more than one kind of quantum fluid which can serve as a transducer between EM and GR waves.

Like superfluids, the quantum Hall fluid is an example of a quantum fluid which differs from a classical fluid in its current-current correlation function in the presence of GR waves. In particular, GR waves can induce a transition of the quantum Hall fluid out of its ground state *only* by exciting a quantized, collective excitation, such as the vortex-like $\frac{1}{3}e$ quasi-particle, across the quantum Hall energy gap. This collective excitation would involve the correlated motions of a macroscopic number of electrons in this coherent quantum system. Hence the quantum Hall fluid, like the other quantum fluids, should be effectively incompressible and dissipationless, and is thus a good candidate for a quantum antenna and transducer.

There exist other situations in which a minimal-coupling rule similar to the one above, arises for *scalar* quantum fields in curved spacetime. DeWitt[13] suggested in 1966 such a coupling in the case of superconductors. Speliotopoulos noted in 1995[14] that a cross-coupling term of the form $H_{int} \sim \mathbf{a} \cdot \mathbf{b}$ arose in the long-wavelength approximation of a certain quantum Hamiltonian derived from the geodesic deviation equations of motion using the transverse-traceless gauge for GR waves.

Speliotopoulos and I have been working on the problem of the coupling of a scalar quantum field to curved spacetime in a general laboratory frame, which avoids the use of the long-wavelength approximation.[15] In general relativity, there exists in general no global time coordinate that can apply throughout a large system, since for nonstationary metrics, such as those associated with gravitational radiation, the local time axis varies from place to place in the system. It is therefore necessary to set up operationally a general laboratory frame by which an observer can measure the motion of slowly moving test particles in the presence of weak, time-varying gravitational radiation fields.

For either a classical or quantum test particle, the result is that its mass m should enter into the Hamiltonian through the replacement of $\mathbf{p} - e\mathbf{A}$ by $\mathbf{p} - e\mathbf{A} - m\mathbf{N}$, where $\mathbf{N}$ is the small, local tidal velocity field induced by gravitational radiation on a test particle located at X_a relative to the observer at the origin (i.e., the center of mass) of this frame, where, for the small deviations h_{ab} of the metric from that of flat spacetime,

$$N_a = \frac{1}{2} \int_0^{X_a} \frac{\partial h_{ab}}{\partial t} dX^b. \tag{10}$$

Due to the quadrupolar nature of gravitational tidal fields, the velocity field $\mathbf{N}$ for a plane wave grows linearly in magnitude with the distance of

the test particle as seen by the observer located at the center of mass of the system. Therefore, in order to recover the standard result of classical GR that only *tidal* gravitational fields enter into the coupling of radiation and matter, one expects in general that a new characteristic length scale L corresponding to the typical size of the distance X_a separating the test particle from the observer, must enter into the determination of the coupling constant between radiation and matter. For example, L can be the typical size of the detection apparatus (e.g., the length of the arms of the Michelson interferometer used in LIGO), or of the transverse Gaussian wave packet size of the gravitational radiation, so that the coupling constant associated with the Feynman vertex for a graviton-particle interaction becomes proportional to the *extensive* quantity $\sqrt{G}L$, instead of an *intensive* quantity involving only $\sqrt{G}$. For the case of superconductors, treating Cooper pairs of electrons as bosons, we would expect the above arguments would carry over with the charge e replaced by $2e$ and the mass m replaced by $2m$.

4 An experiment using YBCO as transducers between GR and EM waves

4.1 Motivation and idea of the experiment

Motivated by the above theoretical considerations, we performed an experiment using a high T_c superconductor, yttrium barium copper oxide (YBCO), as one such possible quantum transducer, in a first attempt to observe the predicted quantum transduction process from EM to GR waves, and vice versa. We chose YBCO because it allowed us to use liquid nitrogen as the cryogenic fluid for cooling the sample down below $T_c = 90$ K to achieve macroscopic quantum coherence, which is much simpler to use than liquid helium. Although we did not observe a detectable conversion signal in this first experiment, we did establish an upper bound on the transducer conversion efficiency of YBCO, and the techniques we used in this experiment could prove to be useful in future experiments.

The idea of the experiment was as follows: Use a first YBCO sample to convert EM into the GR radiation by shining microwaves onto it, and use a second sample to back-convert the GR radiation generated in the far field by the first sample back into EM radiation of the original frequency. In this way, GR radiation could be generated by the first YBCO sample as the *source* of such radiation inside a first closed metallic container, and GR radiation could be detected by the second sample as the *receiver* of such radiation inside a second closed metallic container, in a Hertz-type experiment.

The electromagnetic coupling between the two halves of the apparatus containing the two YBCO samples, called the "Emitter" and the "Receiver," respectively, could be prevented by means of two Faraday cages, i.e., the two closed metallic cans which completely surrounded the two samples and their associated microwave equipment. See Fig.2. The Faraday cages consisted of two empty one-gallon paint cans with snugly fitting cover lids, whose inside walls, cover lids, and can bottoms, were lined on

their interiors with a microwave-absorbing foam-like material (Eccosorb AN70), so that any microwaves incident upon these walls were absorbed. Thus multiply-reflected EM microwave radiation within the cans could thereby be effectively eliminated.

The electromagnetic coupling between the two cans with their cover lids on, was measured to be extremely small (see below). Since the Faraday cages were made out of normal metals, and the Eccosorb materials were also not composed of any macroscopically coherent quantum matter, these shielding materials should have been essentially transparent to GR radiation. Therefore, we would expect that GR radiation should have been able to pass through from the source can to the receiver can without much attenuation.

A simplified schematic outlining the Hertz-type experiment is shown in Fig.2, in which gravitational radiation at 12 GHz could be emitted and received using two superconductors. The "Microwave Source" in this Figure generated electromagnetic radiation at 12 GHz ("EM wave"), which was directed onto Superconductor A (the first piece of YBCO) immersed in liquid nitrogen, and would be converted upon reflection into gravitational radiation ("GR wave").

The GR wave, but not the EM wave, could pass through the "Faraday Cages." In the far field of Superconductor A, Superconductor B (a second piece of YBCO), also immersed in liquid nitrogen, could reconvert upon reflection the GR wave back into an EM wave at 12 GHz, which could then be detected by the "Microwave Detector."

For a macroscopically coherent quantum state in YBCO to be produced, the frequency of the microwaves was chosen to be well below the superconducting gap frequency of YBCO. In order to satisfy this requirement, we chose for our experiment the convenient microwave frequency of 12 GHz (or a wavelength of 2.5 cm), which is three orders of magnitude less than gap frequency of YBCO.

Since the predicted conversion process is fundamentally quantum mechanical in nature, the signal would be predicted to disappear if either of the two samples were to be warmed up above the superconducting transition temperature. Hence the signal at the microwave detector should disappear once either superconductor was warmed up above its transition temperature, i.e., after the liquid nitrogen boiled away in either dewar containing the YBCO samples.

It should be emphasized that the predicted quantum transducer conversion process involves a linear relationship between the amplitudes of the two kinds of radiation fields (EM and GR), since we are considering the linear response of the first sample to the incident EM wave during its generation of the outgoing GR wave, and also the linear response of the second sample to the incident GR wave during its generation of the outgoing EM wave. Time-reversal symmetry, which has been observed to be obeyed by EM and GR interactions at low energies for classical fields, would lead us to expect that these two transducer conversion processes obey the principle of reciprocity, so that the reverse process should have an efficiency equal to that of the forward process. However, it should be noted that although time-reversal symmetry for EM interactions has been extensively experimentally tested, it has not been as well tested for GR
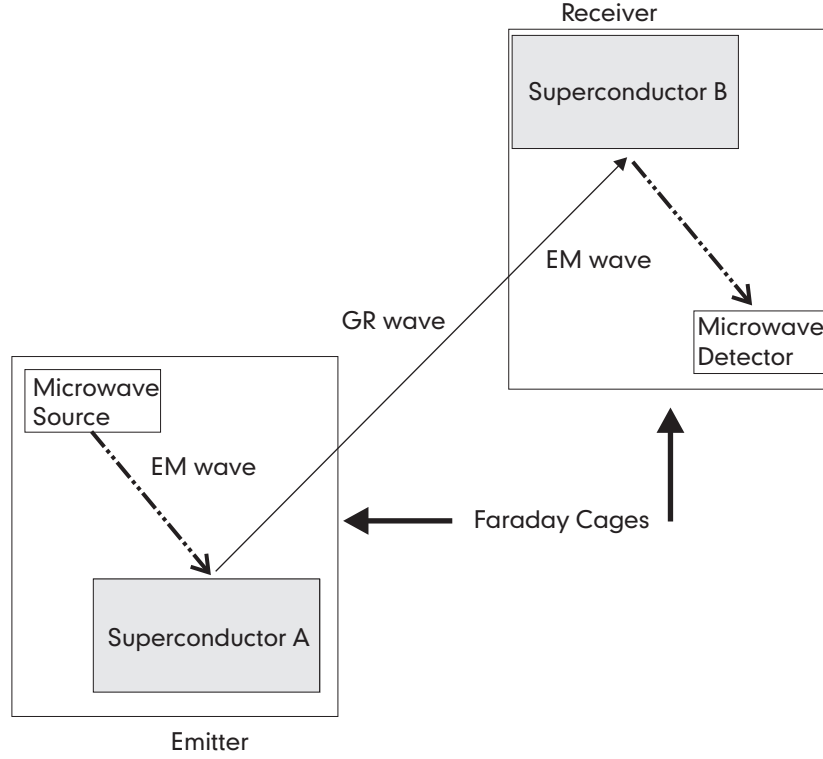
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Figure 2: Simplified schematic of a Hertz-type experiment, in which gravitational radiation at 12 GHz could be emitted and received using two superconductors. The "Microwave Source" generated electromagnetic radiation at 12 GHz ("EM wave"), which impinged on Superconductor A, could be converted upon reflection into gravitational radiation ("GR wave"). The GR wave, but not the EM wave, could pass through the "Faraday Cages." In the far field of Superconductor A, Superconductor B could reconvert upon reflection the GR wave back into an EM wave at 12 GHz, which could then be detected by the "Microwave Detector."
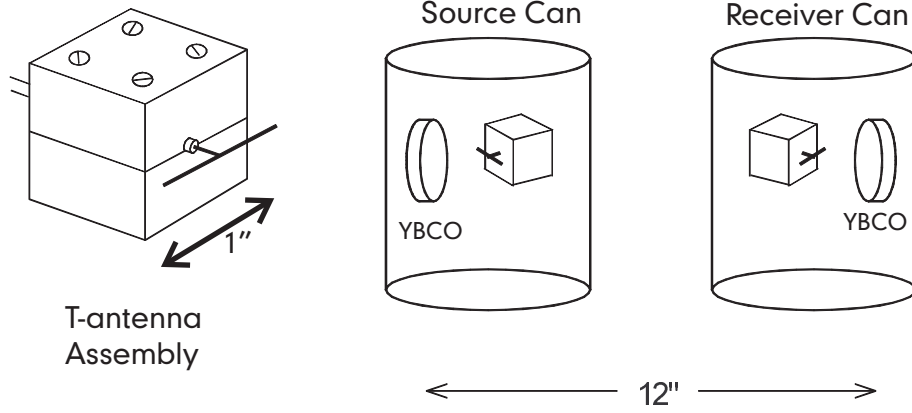
Figure 3: The T-antenna (expanded view on the left) used as antennas inside the "Source Can" and the "Receiver Can." The YBCO samples were oriented so that a GR microwave beam could be directed from one YBCO sample to the other along a straight line of sight.

interactions.

Thus, assuming that the two samples are identical, we expect that the overall power conversion efficiency of this Hertz-type experiment η_{Hertz} should be

$$\eta_{Hertz} = \eta_{EM \to GR} \cdot \eta_{GR \to EM} = \eta^2 \qquad (11)$$

where $\eta_{EM \to GR}$ is the EM-to-GR power conversion efficiency by the first sample, and $\eta_{GR \to EM}$ is the GR-to-EM power conversion efficiency of the second sample. If the two samples are closely similar to each other, we expect that $\eta_{EM \to GR} = \eta_{GR \to EM} = \eta$, where η is the transducer power conversion efficiency of a given sample. Hence, the overall efficiency should be $\eta_{Hertz} = \eta^2$.

5 Experimental details

5.1 The T antennas

In the case of the quantum Hall fluid considered earlier, the medium would have a strong magnetic field applied to it, so that the conservation of total angular momentum during the conversion process between the spin-1 EM field and the spin-2 GR field, could be satisfied by means of the angular momentum exchange between the fields and the anisotropic quantum Hall medium. Here, however, our isotropic, compressed-powder YBCO medium did not have a magnetic field applied to it in our initial experiments, so that it was necessary to satisfy the conservation of angular momentum in another way: One must first convert the EM field into an angular-momentum 2, quadrupolar, far-field radiation pattern.

This was accomplished by means of a T-shaped electromagnetic antenna, which generated in the far field an quadrupolar EM field pattern

that matched that of the quadrupolar GR radiation field pattern. In order to generate a quadrupolar EM radiation field, it is necessary to use an antenna with structure possessing an even-parity symmetry. This was implemented by soldering onto the central conductor of a SMA coaxial cable a one-wavelength-long wire extending symmetrically on either side of the central conductor in opposite directions, in the form of a T-shaped antenna (see Fig.**??**).

A one-inch cube aluminum block assembly was placed at approximately a quarter of a wavelength behind the "T," so as to reflect the antenna radiation pattern into the forwards direction, and also to impedance-match the antenna to free space. The aluminum block assembly consisting of two machined aluminum half-blocks which could be clamped tightly together to fig snugly onto the outer conductor of the SMA coaxial cable, so as to make a good ohmic contact with it. The joint between the two aluminum half-blocks was oriented parallel to the bar of the "T." Thus the block formed a good ground plane for the antenna. The resonance frequency of this T-antenna assembly was tuned to be 12 GHz, and its Q was measured to be about 10, using a network analyzer (Hewlett Packard model HP8720A).

Measurements of the radiative coupling between two such T antennas placed directly facing each other at a fixed distance, while varying their relative azimuthal angle, showed that extinction between the antennas occured at a relative azimuthal angle of $45°$ between the two "T"s, rather than at the usual $90°$ angle expected for dipolar antennas. Furthermore, we observed that at a mutual orientation of $90°$ between the two T antennas (i.e., when the two "T"s were crossed with respect to each other), a *maximum* in the coupling between the antennas, in contrast to the *minimum* expected in the coupling between two crossed linear dipole antennas. This indicates that our T antennas were indeed functioning as quadrupole antennas. Thus, they would generate a quadrupolar pattern of EM radiation fields in the far field, which should be homologous to that of GR radiation.

5.2   The 12 GHz microwave source

For generating the 12 GHz microwave beam of EM radiation, which we used for shining a beam of quadrupolar radiation on the first YBCO sample, we started with a 6 GHz "brick" oscillator (Frequency West model MS-54M-09), with an output power level of 13 dBm at 6 GHz. This 6 GHz signal was amplified, and then doubled in a second harmonic mixer (MITEQ model MX2V080160), in order to produce a 12 GHz microwave beam with a power level of 7 dBm. The 12 GHz microwaves was fed into the T antenna that shined a quadrupolar-pattern beam of EM radiation at 12 GHz onto the first YBCO sample immersed in a liquid nitrogen dewar inside the source can. The sample was oriented so as to generate upon reflection a 12 GHz GR radiation beam directed towards the second YBCO sample along a line of sight inside the receiver can (see Fig.**??**).

The receiver can contained the second YBCO sample inside a liquid nitrogen dewar, oriented so as to receive the beam of GR, and back-convert it into a beam of EM radiation, which was directed upon reflection towards
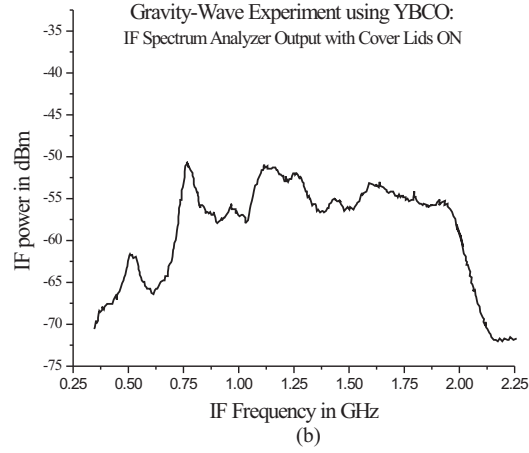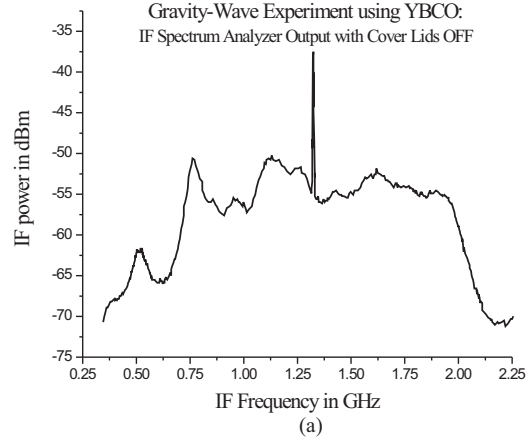
Figure 4: Data from the Hertz-type gravity-wave experiment using YBCO superconductors as transducers between EM and GR radiation. In (a), the cover lids were off both the source and the receiver cans, so that a small leakage signal (the central spike) could serve to test the system. In (b), both cover lids were on the cans, but no detectable signal of coupling between the cans could be seen above the noise. Both YBCO samples were immersed in liquid nitrogen for these data.

a second T antenna. A low-noise preamp (Astrotel model PMJ-LNB KU, used for receiving 12 GHz microwave satellite communications), which had a noise figure of 0.6 dB, was used as the first-stage amplifier of the received signal. This noise temperature determined the overall sensitivity of the measurement. This front-end LNB (Low-Noise Block) assembly, besides having a low-noise preamp, also contained inside it an internal mixer that down-converted the amplified 12 GHz signal into a standard 1 GHz IF (Intermediate Frequency) band. We then fed this IF signal into a commercial satellite signal level meter (Channel Master model 1005IFD), which both served as the DC power supply for the LNB assembly by supplying a DC voltage back through the center conductor of a F-style IF coax cable into the LNB assembly, and also provided amplification of the IF signal. Its output was then fed into a spectrum analyzer (Hewlett-Packard model 8559A).

5.3   The liquid nitrogen dewars

In order for the YBCO samples (1 inch diameter, 1/4 inch thick pieces of high-density YBCO) to become superconducting, we cooled these samples to 77K by immersing them in liquid nitrogen. The dewars needed for holding this cryogenic fluid together with the YBCO samples consisted of a stack of styrofoam cups; the dead air space between the cups, which were glued together at their upper lips, served as good thermal insulation.

The samples were epoxied in a vertical orientation into a slot in a styrofoam piece which fit snugly into the bottom of the top cup of the stack, and the cups also fit snugly into a hole in the top layer of Eccosorb foam pieces placed at the bottom of the can. Also, since styrofoam was transparent to microwave radiation, these cup stacks also served as convenient *dielectric* dewars for holding the YBCO samples in liquid nitrogen. At the beginning of a run, we would pour into these cups liquid nitrogen, which would last about a hour before it boiled away. The temperatures of the samples were monitored by means of thermocouples attached to the back of the samples.

6   Data

We show in part (a) of Fig.4 data showing the IF spectrum analyzer output of the signal from the receiver can with the cover lids *off* both the source can and the receiver can, which allowed a small leakage signal to be coupled between the two cans (to test whether the entire system was working properly), and in part (b), data with covers lids *on* both cans. Both YBCO samples were immersed in liquid nitrogen for both (a) and (b). The data in (b) show that the Eccosorb-lined Faraday cages were very effective in screening out any electromagnetic pickup. However, there is no detectable signal above the noise that would indicate any detectable coupling due to the quantum transducer conversion between EM and GR waves. Before taking these data, we tested *in situ* that when they immersed in liquid nitrogen, the YBCO samples were indeed in a superconducting state by the observation of a repulsion away from the YBCO

of a small permanent magnet hung by means a string near the samples.

The sensitivity of the source-receiver system was calibrated in a separate experiment, in which we replaced the two T antennas by a low-loss cable directly connecting the source to the receiver, in series with 70 dB of calibrated attenuation. We could then measure the size of this directly coupled 12 GHz electromagnetic signal on the spectrum analyzer with respect to the noise rise, which served as a convenient measure of the minimum detectable signal strength. In the resulting spectrum, which was similar to that shown in Fig.4(a), we observed a -77 dBm central peak at 12 GHz, which was 25 dB above the noise rise. This implies that we could have seen a signal of -102 dBm of transducer-coupled radiation with a signal-to-noise ratio of about unity. Assuming that the T antennas were perfectly efficient in coupling to the YBCO samples, from the data shown in Fig.4 we would infer that the observed efficiency η_{Hertz} was less than 95 dB, and therefore from Eq.(11), that the quantum transducer efficiency η was less than 48 dB, i.e., $\eta < 1.6 \times 10^{-5}$.

7   Conclusions

Why did we even bother performing this transducer experiment, when we knew that Faraday cages were essentially perfect shields, and therefore that there seemingly should have been no coupling at all between the two cans? The first answer: Even classically, one expects a *nonzero* coupling between the cans due to the fact that accelerated electrons produce a *nonvanishing* amount of GR radiation, since each electron possesses a mass m, as well as a charge e. Therefore, whenever an electron's charge undergoes acceleration, so will its mass. Relativistic causality therefore necessitates that changes in the gravitational field of an electron in the radiation zone due to its acceleration must be retarded by the speed of light, just like the electromagnetic field in the radiation zone. This implies that there must exist a transducer power conversion efficiency of at least $Gm^2 \cdot 4\pi\varepsilon_0/e^2 = 2.4 \times 10^{-43}$, based on a naive classical picture in which each individual electron possesses a deterministic, Newtonian trajectory. Thus even in principle, the Faraday cages could not have provided a perfect shielding between the two cans. However, if this classical picture had been correct, there would have been no hope of actually observing this conversion process, based on the sensitivity of existing experimental techniques such as those described above.

The second answer: Superconductivity is fundamentally a quantum mechanical phenomenon. Due to the macroscopic coherence of the ground state with ODLRO, and the existence of a non-zero energy gap, there may exist quantum many-body enhancements to this classical conversion efficiency. In addition to these enhancements, there must exist additional enhancements due to the fact that the intensive coupling constant $\sqrt{G}$ of the Feynman graviton-matter vertex should be replaced by the extensive coupling constant $\sqrt{G}L$, in order to account correctly for the *tidal* nature of GR waves [15].

The third answer: The justification for this experiment ultimately is that the ground state of a superconductor, which possesses spontaneous

symmetry breaking, and therefore off-diagonal long-range order, is very similar to that of the physical vacuum, which is believed also to possess spontanous symmetry breaking through the Higgs mechanism. In this sense, therefore, the vacuum is "superconducting." The question thus arises: How does such a broken-symmetry ground, or "vacuum," state interact with a dynamically changing spacetime, such as that associated with a GR wave? More generally: How do we embed quantum fields in dynamically curved spacetimes? We believe that this question has never been explored before *experimentally*.

How then do we account for the lack of any observable quantum transducer conversion in our experiment? There are several possible reasons, the most important ones probably having to do with the material properties of the YBCO medium. One such possible reason is the earlier observations of unexplained residual microwave and far-infrared losses (of the order of 10^{-5} ohms per square at 10 GHz) in YBCO and other high T_c superconductors, which are independent of temperature and have a frequency-squared dependence,[16] which may be due to the fact that YBCO is a D-wave superconductor.[17] In D-wave superconductors, there exists a four-fold symmetry of nodal lines along which the BCS gap vanishes,[18] where the microwave attenuation may become large. Thus D-wave superconductors are quite unlike the classic, low-temperature S-wave superconductors with respect to their microwave losses. Since one of conditions for a good coupling of a quantum antenna and transducer to the GR wave sector is extremely low dissipative losses, the choice of YBCO as the material medium for the Hertz-type experiment may not have been a good one.

8   Acknowledgments

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